Cambridge

IGCSE

Physics

CODE: (9702)

Chapter 16

Radioactivity

Looking inside the atom

The idea that matter is composed of very small particles called atoms was first suggested by the Greeks some 2000 years ago. However, it was not until the middle of the 19th century that any ideas about the inside of the atom were proposed.

Figure 16.2 Ernest Rutherford (on the right) in the Cavendish Laboratory, Cambridge, England. He had a loud voice that could disturb sensitive apparatus and so the notice was a joke aimed at him.

J.J. Thomson proposed the atom as a neutral particle with positive and negative charges, known as the **plum pudding model**. The electron, with a mass of 9.11×10−31 kg and a charge of −1.60×10−19C, is now used to explain electrostatics, current electricity, and electronics.

Alpha-particle scattering and the nucleus

In 1906, while experimenting with the passage of α-particles through a thin mica sheet, Ernest Rutherford (Figure 16.2) noticed that most of the α-particles passed straight through. This suggested to him that there might be a large amount of empty space in the atom, and by 1909 he had developed what we now call the **nuclear model of the atom.**

Some were deflected slightly, but about 1 in 20 000 were deflected through an angle of more than 90°, so that they appeared to bounce back off the foil. This helped to confirm Rutherford in his thinking about the atom – that it was mostly empty space, with most of the mass and all of the positive charge concentrated in a tiny region at the centre. This central **nucleus** only affected the α-particles when they came close to it.

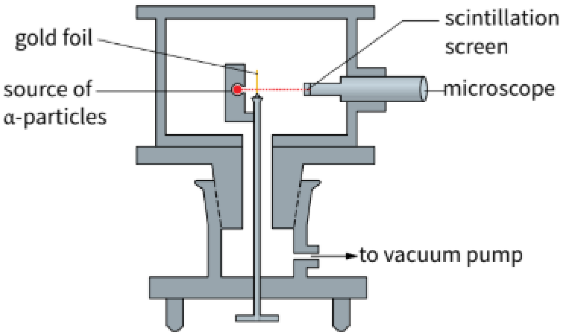

Figure 16.3 The apparatus used for the α-scattering experiment. The microscope can be moved round to detect scattered radiation at different angles.

Figure 16.3 shows the apparatus used in the α-scattering experiment. Notice the following points:

■■ The α-particle source was encased in metal with a small aperture, allowing a fine beam of α-particles to emerge.

■■ Air in the apparatus was pumped out to leave a vacuum; α-radiation is absorbed by a few centimetres of air.

■■ One reason for choosing gold was that it can be made into a very thin sheet or foil. Rutherford's foil was only a few hundreds of atoms thick.

■■ The α-particles were detected when they struck a solid 'scintillating' material. Each α-particle gave a tiny flash of light and these were counted by the experimenters (Geiger and Marsden).

■■ The detector could be moved round to detect α-particles scattered through different angles.

Explaining α-scattering

The back-scattering of α-particles by gold atoms can be explained by the electrostatic repulsion between the positive charge of the α-particle and the positive charge of the atom's nucleus. If the atom were a bullet with negatively charged electrons scattered through a positive charge, an α-particle would pass through it without deflecting. However, if the mass and positive charge were concentrated at one point, an α-particle would strike something more massive and with a greater charge, sending it backwards.

BOX 16.1: An analogy for Rutherford scattering

A very simple analogy (or model) of the experiment is shown in Figure 16.4. When you roll a ball-bearing down a slope towards the 'cymbal', it may be deflected, but even if it is rolled directly at the cymbal's centre, it does not come back – it rolls over the centre and carries on to the other side. However, using the 'tin hat' shape, with a much narrower but higher central bulge, any ball-bearings rolled close to the centre will be markedly deflected, and those rolled directly towards it will come straight back.

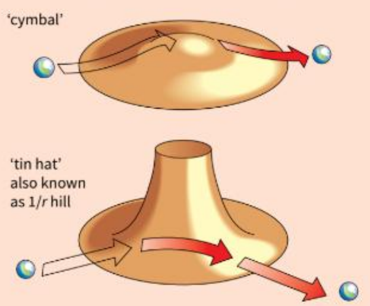

Figure 16.4 An analogy for Rutherford's experiment.

The shape of the cymbal represents the shape of the electric field of an atom in the 'plum pudding' model: low central intensity and spread out. The 'tin hat' represents the shape of the electric field for the nuclear model: high central intensity and concentrated.

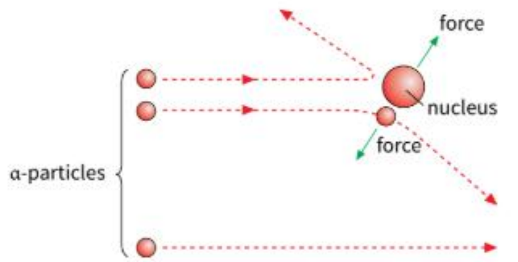

Figure 16.5 Possible paths of an α-particle near a nucleus. The nucleus and the α-particle both experience electrostatic repulsion.

From the α-particle scattering experiment, Rutherford deduced the following.

- An α-particle is deviated due to the repulsive force between the α-particle and the positive charge in the atom.
- Most α-particles have little or no deviation – so most of an atom is empty space.
- A very few α-particles are deviated more than 90° – so most of the mass of an atom is concentrated in a small space (the nucleus) and most of the atom is empty space.

A simple model of the atom

Rutherford's nuclear model of the atom gained acceptance due to its explanation of chemical bonding. The proton, with a positive charge, was discovered, but its mass was too small to account for the atom's entire mass. The neutron solved this puzzle in the early 1930s.

■■ Protons and neutrons make up the nucleus of the atom.

■■ The electrons move around the nucleus in a cloud, some closer to and some further from the centre of the nucleus.

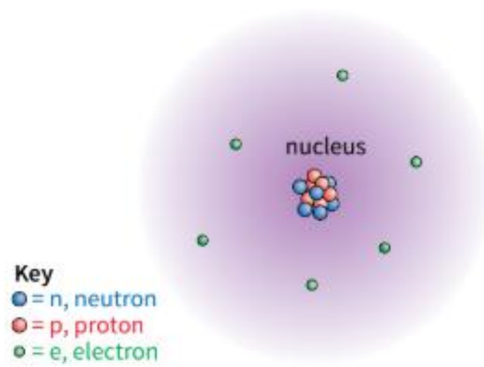

Figure 16.6 A simple model of the atom. If the nucleus were drawn to scale, it would be invisible (and the electrons are even smaller!).

The scale of things

It is useful to have an idea of the approximate sizes of typical particles:

- radius of proton ~ radius of neutron ~ 10^{-15} m
- radius of nucleus ~ 10^{-15} m to 10^{-14} m
- radius of atom ~ 10^{-10} m
- size of molecule ~ 10^{-10} m to 10^{-6} m.

(Some molecules, such as large protein molecules, are very large indeed – compared to an atom!)

The radii of nuclear particles are often quoted in femtometres (fm), where 1 fm = 10^{-15} m.

Nuclear density

We can picture a proton as a small, positively charged sphere. Knowing its mass and radius, we can calculate its density:

mass of proton $m_p = 1.67 \times 10^{-27}$ kg

radius of proton $r = 0.80\,\text{fm} = 0.80 \times 10^{-15}$ m

(In fact, the radius of the proton is not very accurately known; it is probably between 0.80×10^{-15} m and 0.86×10^{-15} m.)

$$\text{volume of proton} = \tfrac{4}{3}\pi r^3 = \tfrac{4}{3}\pi \times (0.80 \times 10^{-15})^3$$

$$= 2.14 \times 10^{-45}\,\text{m}^3 \approx 2.1 \times 10^{-45}\,\text{m}^3$$

$$\text{density} = \frac{\text{mass}}{\text{volume}}$$

$$\text{density} = \frac{1.67 \times 10^{-27}}{2.14 \times 10^{-45}} \approx 7.8 \times 10^{17}\,\text{kg m}^{-3}$$

Nucleons and electrons

We will start this section with a summary of the particles mentioned so far (Table 16.1). All nuclei, except the lightest form of hydrogen, contain protons and neutrons, and each nucleus is described by the number of protons and neutrons that it contains.

■■ Protons and neutrons in a nucleus are collectively called nucleons. For example, in a nucleus of gold, there are 79 protons and 118 neutrons, giving a total of 197 nucleons altogether.

■■ The total number of nucleons in a nucleus is called the nucleon number (or mass number) A.

■■ The nucleon number is equal to the sum of the number of neutrons in the nucleus, the neutron number N, and the number of protons, the proton number (or atomic number)

Particle	Relative mass (proton = 1)[a]	Charge[b]
proton (p)	1	$+e$
neutron (n)	1	0
electron (e)	0.0005	$-e$
alpha-particle (α)	4	$+2e$

[a]The numbers given for the masses are approximate.
[b]$e = 1.60 \times 10^{-19}$ C.

Table 16.1 Summary of the particles that we have met so far in this chapter. The α-particle is in fact a helium nucleus (with two protons and two neutrons).

Isotopes are nuclei of the same element with different numbers of neutrons but the same number of protons.

The nucleus of any atom can be represented by the symbol for the element along with the nucleon number and proton number, as shown below:

$^{\text{nucleon number}}_{\text{proton number}}$element symbol $^{A}_{Z}X$

oxygen $^{16}_{8}O$ gold $^{197}_{79}Au$ uranium $^{238}_{92}U$

A specific combination of protons and neutrons in a nucleus is called a **nuclide**.

The proton and nucleon numbers of some common nuclides are shown in Table 16.2.

Isotopes

Although atoms of the same element may be identical chemically, their nuclei may be slightly different. The number of protons in the nucleus of an atom determines what element it is: helium always has 2 protons, carbon 6 protons, oxygen 8 protons, neon 10 protons, radium 88 protons, uranium 92 protons, and so on.

$^{20}_{10}Ne$ $^{21}_{10}Ne$ $^{22}_{10}Ne$

The first has 10 neutrons in the nucleus, the second 11 neutrons and the third 12 neutrons. These three types of neon nuclei are called **isotopes** of neon.

Element	Nucleon number *A*	Proton number *Z*	Element	Nucleon number *A*	Proton number *Z*
hydrogen	1	1	bromine	79	35
helium	4	2	silver	107	47
lithium	7	3	tin	120	50
beryllium	9	4	iodine	130	53
boron	11	5	caesium	133	55
carbon	12	6	barium	138	56
nitrogen	14	7	tungsten	184	74
oxygen	16	8	platinum	195	78
neon	20	10	gold	197	79
sodium	23	11	mercury	202	80
magnesium	24	12	lead	206	82
aluminium	27	13	bismuth	209	83
chlorine	35	17	radium	226	88
calcium	40	20	uranium	238	92
iron	56	26	plutonium	239	94
nickel	58	28	americium	241	95

Table 16.2 Proton and nucleon numbers of some nuclides.

Atoms are electrically neutral, with the number of electrons surrounding the nucleus equal to the number of protons. The chemical properties of an atom are determined by the number of protons and electrons, while the nuclear properties are determined by the number of neutrons. Isotopes of the same element have identical chemical properties but differ in nuclear properties. Hydrogen is the most abundant element due to its simple structure.

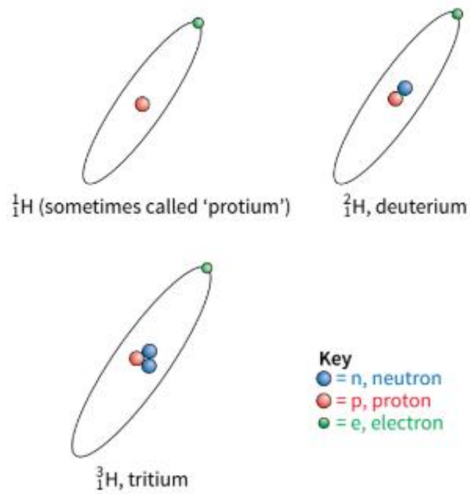

Figure 16.7 The isotopes of hydrogen.

Figure 16.8 The Horsehead Nebula in Orion. The large coloured regions are expanses of dust and gas, mostly hydrogen, that are ionised by nearby stars so that they emit light. The dark 'horse head' is where the areas of gas and dust remain in atomic form and block out the light from behind.

Forces in the nucleus

The nucleus of an atom contains protons and neutrons, with protons carrying positive charge and neutrons uncharged. The nucleus holds together despite electrostatic repulsions, indicating an attractive force between the nucleons.

This is called the strong nuclear force. It only acts over very short distances (10–$^{14\mathrm{m}}$), and it is what holds the nucleus together.

Diluting the protons

In small nuclei the strong nuclear force from all the nucleons reaches most of the others in the nucleus, but as we go on adding protons and neutrons the balance becomes much finer.

Most atoms that make up our world have stable nuclei; that is, they do not change as time goes by, which is quite fortunate really! However, some are less stable and give out radiation. Whether or not an atom is unstable depends on the numbers of protons and neutrons in its nucleus. Hydrogen-1 (1p), helium-4 (2p, 2n), carbon-12 (6p, 6n) and oxygen-16 (8p, 8n) are all stable – but add or subtract neutrons and the situation changes.

Table 16.3 gives details of some other commonly occurring isotopes.

Element	Nucleon number *A*	Proton number *Z*	Neutron number *N*
hydrogen	1	1	0
	2	1	1
carbon	12	6	6
	14	6	8
oxygen	16	8	8
	18	8	10
neon	20	10	10
	21	10	11
potassium	39	19	20
	40	19	21
strontium	88	38	50
	90	38	52
caesium	135	55	80
	137	55	82
lead	206	82	124
	208	82	126
radium	226	88	138
	228	88	140
uranium	235	92	143
	238	92	146

Table 16.3 Some commonly occurring isotopes.

Fundamental particles?

Chemistry is very complicated because there are literally billions of different molecules that can exist. The discovery of the Periodic Table simplified things because it suggested that there were roughly 92 different elements whose atoms could be arranged to make these various molecules.

However, in the middle decades of the 20th century, physicists discovered many other particles that did not fit this pattern. They gave them names such as pions, kaons, muons, etc., using up most of the letters of the Greek alphabet.

These new particles were found in two ways:

■■ by looking at cosmic rays, which are particles that arrive at the Earth from outer space

■■ by looking at the particles produced by high-energy collisions in particle accelerators (Figure 16.9).

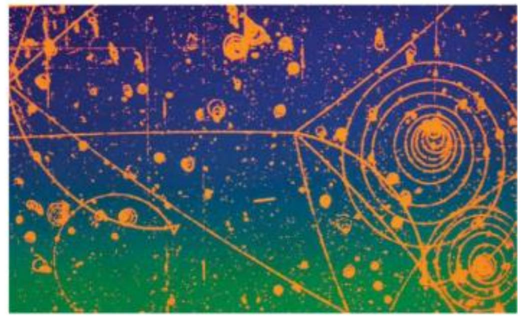

Figure 16.9 Particle tracks in a bubble chamber detector. A particle has entered from the left and then struck another particle just to the right of the centre. Four new particles fly out from the point of impact.

Figure 16.10 Particle accelerators have become bigger and bigger as scientists have sought to look further and further into the fundamental nature of matter. This is one of the particle detectors of the Large Hadron Collider (LHC), as it was about to be installed. The entire collider is 27 km in circumference.

Families of particles

Today, sub-atomic particles are divided into two families:

■■ Hadrons such as protons and neutrons. These are all particles that are affected by the strong nuclear force.

■■ Leptons such as electrons. These are particles that are unaffected by the strong nuclear force.

Inside hadrons

To sort out the complicated picture of the hadron family of particles, Murray Gell-Mann in 1964 proposed a new model. He suggested that they were made up of just a few different particles, which he called **quarks**.

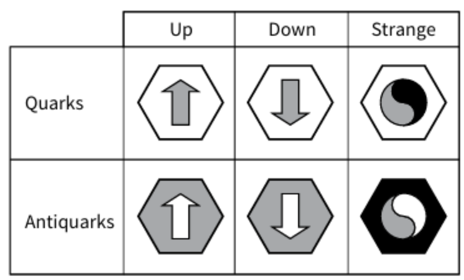

Figure 16.11 Icons representing three 'flavours' of quark, up, down and strange, and their antiquarks.

Gell-Mann's idea was that there are two types of hadron: baryons, made up of three quarks, and mesons, made up of two quarks. In either case, the quarks are held together by the strong nuclear force.

Discovering radioactivity

The French physicist Henri Becquerel (Figure 16.12) is credited with the discovery of radioactivity in 1896. He had been looking at the properties of uranium compounds when he noticed that they affected photographic film – he realised that they were giving out radiation all the time and he performed several ingenious experiments to shed light on the phenomenon.

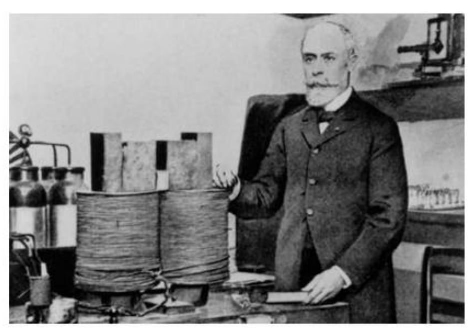

Figure 16.12 Henri Becquerel, the discoverer of radioactivity, in his laboratory. His father and grandfather had been professors of physics in Paris before him.

Radiation from radioactive substances

There are three types of radiation which are emitted by radioactive substances: alpha (α), beta (β) and gamma (γ) radiations come from the unstable nuclei of atoms.

However, there are also many unstable nuclei that emit beta-plus (β+) radiation. This radiation is in the form of positrons, similar to electrons in terms of mass but with positive charge of +e. **Positrons** are a form of **antimatter**

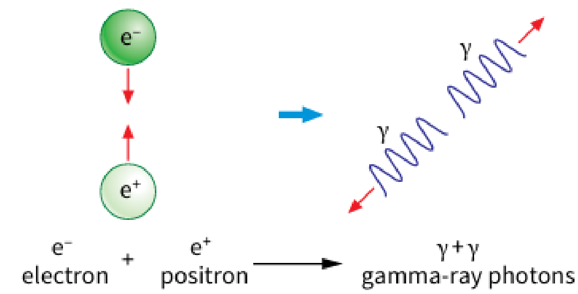

Figure 16.13 Energy is released in the annihilation of matter and antimatter.

Table 16.4 shows the basic characteristics of the different types of radiation. The masses are given relative to the mass of a proton; charge is measured in units of e, the elementary charge.

Radiation	Symbol	Mass (relative to proton)	Charge	Typical speed
α-particle	α, ${}^{4}_{2}He$	4	+2*e*	'slow' ($10^6\,m\,s^{-1}$)
β^--particle	β, β^-, e, ${}^{0}_{-1}e$	$\frac{1}{1840}$	−*e*	'fast' ($10^8\,m\,s^{-1}$)
β^+-particle	β, β^+, e+, ${}^{0}_{+1}e$	$\frac{1}{1840}$	+*e*	'fast' ($10^8\,m\,s^{-1}$)
γ-ray	γ	0	0	speed of light ($3 \times 10^8\,m\,s^{-1}$)

Table 16.4 The basic characteristics of ionising radiations.

Note the following points:

- α- and β-radiation are particles of matter. A γ-ray is a photon of electromagnetic radiation, similar to an X-ray. (X-rays are produced when electrons are decelerated; γ-rays are produced in nuclear reactions.)
- An α-particle consists of two protons and two neutrons; it is a nucleus of helium-4. A β^--particle is simply an electron and a β^+-particle is a positron.
- The mass of an α-particle is nearly 10 000 times that of an electron and it travels at roughly one-hundredth of the speed of an electron.

Discovering neutrinos

There is a further type of particle which we need to consider. These are the **neutrinos**. When β decay was first studied, it was realised that β-particles were electrons coming from the nucleus of an atom.

It was noticed that β-particles were emitted with a **range** of speeds – some travelled more slowly than others

This particle is now known as the **antineutrino** (or, more correctly, the electron antineutrino), with symbol ν–. The decay equation for β– decay is written as:

$$\text{beta-minus } (\beta^-) \text{ decay:} \quad {}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + \bar{\nu}$$

In β+ decay, a proton decays to become a neutron and an **electron neutrino** (symbol ν) is released:

$$\text{beta-plus } (\beta^+) \text{ decay:} \quad {}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e + \nu$$

Fundamental families

Electrons and neutrinos both belong to the family of fundamental particles called **leptons**.

Fundamental families

Electrons and neutrinos both belong to the family of fundamental particles called leptons. So, we have two families of fundamental particles, quarks and leptons. How can we understand β decay in terms of these particles? Consider first β− decay, in which a neutron decays. A neutron consists of three quarks (up, down, down or u d d). It decays to become a proton (u u d).

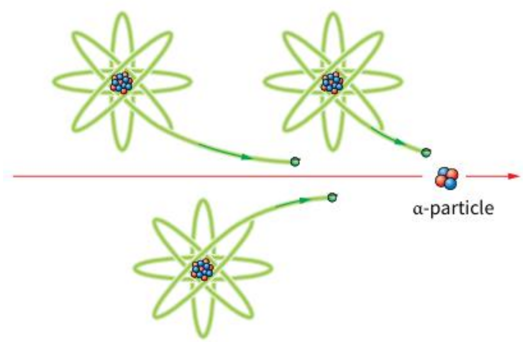

Figure 16.14 As an α-particle passes through a material, it causes ionisation of atoms.

Fundamental forces

The nucleus is held together by the strong nuclear force, acting against the repulsive electrostatic or Coulomb force between protons. This force explains α decay, when a positively charged α-particle flies out of the nucleus, leaving it with less positive charge.

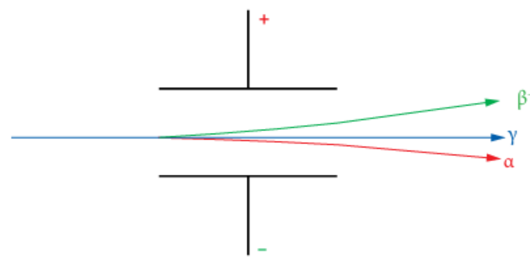

Figure 16.15 An electric field can be used to separate α-, β^-- and γ- radiations. (The deflection of the α-radiation has been greatly exaggerated here.)

Properties of ionising radiation

The resulting atoms are said to be **ionised**, and the process is called ionisation. In the process, the radiation loses some of its kinetic energy. After many ionisations, the radiation loses all of its energy and no longer has any ionising effect.

Behaviour of radiations in electric and magnetic fields

α-, β−-, and γ-radiations have different charges, affecting their behavior in electric and magnetic fields. This helps distinguish radiation types. In an electric field, charged particles attract opposite-charged plates, while β−-particles deflect more due to their mass.

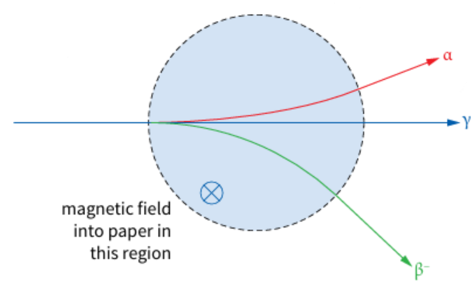

Figure 16.16 A magnetic field may also be used to separate α-, β^-- and γ- radiations. The deflection of the α-radiation has been greatly exaggerated here.

Figure 16.16 shows the effect of a magnetic field. In this case, the deflecting force on the particles is at right angles to their motion.

Radiation penetration

Alpha-radiation

Because α-radiation is highly ionising, it cannot penetrate very far into matter. A cloud chamber can be used to show the tracks of α-particles in air (Figure 16.17). The tracks are very dense, because of the dense concentration of ions produced, and they extend for only a few centimetres into the air.

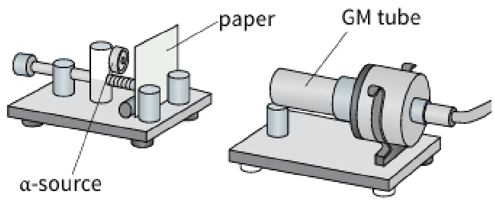

Figure 16.18 Alpha-radiation can be absorbed by a single sheet of paper.

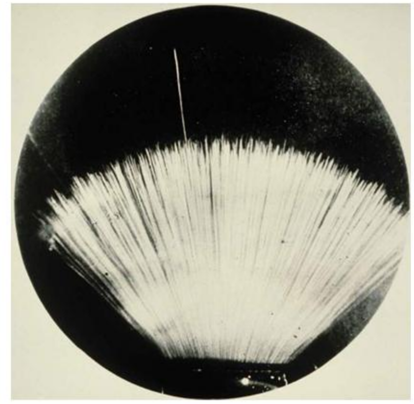

Figure 16.17 Alpha-particle tracks show up in this photograph of a cloud chamber. Notice that all the particles travel roughly the same distance through the air, indicating that they all have roughly the same initial kinetic energy.

Beta-radiation

A Geiger–Müller tube can detect β−-radiation. The source is placed close to the tube, and different materials are positioned between source and tube. Paper has little effect; a denser material such as aluminium or lead is a more effective absorber. A few millimetres of aluminium will almost completely absorb β−-radiation.

Gamma-radiation

Since γ-radiation is the least strongly ionising, it is the most penetrating. Lead can be used to absorb γ-rays. The intensity of the radiation decreases gradually as it passes through the lead.

T he different penetrating properties of α-, β−- and γ-radiations can be summarised as follows:

- α-radiation is absorbed by a thin sheet of paper or a few centimetres of air.
- β^--radiation is absorbed by a few millimetres of metal.
- γ-radiation is never completely absorbed but a few centimetres of lead, or several metres of concrete, greatly reduces the intensity.

This is illustrated in Figure 16.19.

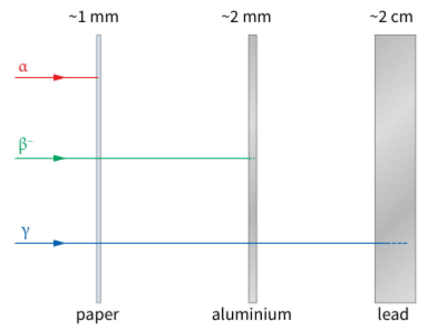

Figure 16.19 A summary of the penetrating powers of α-, β^-- and γ-radiations. The approximate thickness of the absorbing material is also shown.

The electronvolt (eV)

Alpha and beta particles move quickly; gamma photons travel at the speed of light. These types of radiation all have energy, but the energy of a single particle or photon is very small and far less than a joule

When an electron (with a charge of magnitude 1.60×10^{-19} C) travels through a potential difference, energy is transferred. The energy change W is given by:

$$W = QV = 1.60 \times 10^{-19} \times 1 = 1.60 \times 10^{-19}\,\text{J}$$

So we define the electronvolt as follows:

One electronvolt (1 eV) is the energy transferred when an electron travels through a potential difference of one volt.

Therefore:

$$1\ \text{eV} = 1.60 \times 10^{-19}\,\text{J}$$

There is more about the electronvolt and its use in energy calculations in Chapter 30.